



Human Spaceflight Conjunction Operations

*History, Lessons Learned, and Future
Improvements for ISS Debris Avoidance*

SpaceOps 2011 Workshop
June 14-16, 2011

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Evolution of Conjunction Assessment

Initial Operations: Space Shuttle

- Before 1986 Challenger accident, no Shuttle mitigation actions were taken for conjunctions based on assumption that predictions were too imprecise
- After Challenger, analysis led to a “box” method for Shuttle protection

Preparation for ISS operations: the Probability Method

- The 24/7/365 nature of ISS operations meant the box method from Shuttle could not be an option
 - Work began at NASA/JSC in early 1990's to develop infrastructure for “Pc” method
 - NASA provided support to USSPACECOM to develop covariances, computing capability, and “JSpOC” staffing for conjunction detection
- NASA started trial conjunction assessment operations with Russia in 1996 on Mir (“Phase I” program, upon arrival of Americans onboard)
 - Box method always used as trigger to notify Moscow during Mir, and no Russian avoidance maneuver was expected or performed



Evolution of Conjunction Assessment: ISS Operations

Maneuver thresholds determined for ISS

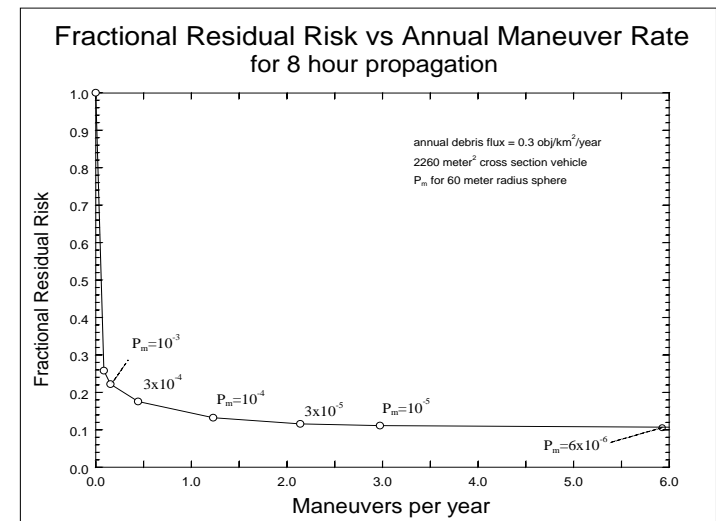
- Balance safety with minimum of operations disruption
- Red threshold of 1-in-10,000: Always maneuver if possible; place crew in Soyuz if maneuver not possible
- Yellow threshold of 1-in-100,000: Maneuver if convenient

Invented Orbital Conjunction Message (OCM) format with USSTRATCOM

Developed “validity criteria” on OCMs to ensure maneuver decisions based on good data

- Requires multiple updates, with prediction variations within expected bounds

Shuttle program and Goddard later adopted probability method for conjunctions



*Example of risk evaluations used to
determine ISS maneuver thresholds*



Developing ISS Operations

International coordination required to establish ISS DAM capability

- ISS has had 6 different vehicles to act as propulsion module, each requiring varying kinds of coordination:
 - *FGB (Zarya) until SM arrival*
 - *Service Module (Zvezda)*
 - *Progress: aft and nadir*
 - *ESA's Automated Transfer Vehicle (ATV)*
 - *Soyuz (contingency; never used)*
 - *Shuttle*
- **Each method (except Shuttle) relies on a planning template requiring >28 hours**



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ISS Debris Avoidance Maneuver History

Date	Debris Object	Vehicle	Notes
06/03/99	1844 (SL-3 R/B)	FGB	Maneuver Execution FAILED. Two PC violations (1E-2 and 1E-3) early in event based on bad data
10/26/99	25422 (Pegasus R/B)	FGB	First successful ISS DAM and only DAM performed by FGB. Highest PC = 1E-03.
09/29/00	5143 (SL-3 R/B)	Progress 1P	Maneuver on Yellow threshold violation
02/10/01	87610 (Unknown Debris)	STS-98 (5A)	Shuttle Box method used
12/15/01	5730 (SL-8 R/B)	STS-108 (UF-1)	Shuttle PC method used
05/15/02	23279 (SL-8 R/B)	Progress 7P	$P_c = 1E-03$ (red threshold violation)
05/30/03	25722 (MEGSAT)	Progress 10P	$P_c = 9E-04$ (red threshold violation)
08/27/08	33246 (COSMOS 2421 Debris)	ATV-1	$P_c = 2E-02$ (red threshold violation) and largest PC calculated to date
03/22/09	26264 (CZ-4 Debris)	STS-119 (15A)	Red threshold violations on a multi-repeating conjunction. TCAs were during an EVA, so a Retrograde DAM was executed early by having orbiter hold attitude.
07/18/09	84180 (Unknown Debris)	STS-127 (2 JA)	TCA occurred 15 hours after STS-127 docking (during crew sleep). Due to the docking perturbations, a red threshold violation was computed and a reboost was performed by the Shuttle before the crew went to sleep.
10/26/10	37195 (UARS Debris)	Progress 39P	$P_c = 5E-03$ (red threshold violation). Probabilities were yellow & red threshold violations throughout the event.
4/2/11	34443 (Cosmos 2251 Debris)	ATV-2	Conjunction with dozens of repeating passes, high drag. Prime TCA shifted later during event

12 ISS debris avoidance maneuvers attempted

7 performed by ISS

1 attempted by ISS, but failed (ISS's first attempt)

4 performed by Shuttle during mated operations



Visiting Vehicle Protection

The Trajectory Operations group (TOPO) at MCC-Houston integrates the trajectories of ISS and all vehicles coming to ISS

In recent years, the TOPO office began implementing debris avoidance support for the operators of these visiting vehicles

- ESA's ATV (1 mission per year)
- JAXA's HTV (1 mission per year)
- Russia's Soyuz and Progress (approximately 7 missions per year)
- Commercial vehicles (SpaceX Dragon and Orbital Cygnus) (1-2 missions per year each)
- *This protects not only the vehicles in rendezvous, but keeps the ISS environment safe as well.*

TOPOs use close relationship with JSpOC to help provide the highest-quality data for use in protecting these vehicles

- Maintain single human spaceflight point of contact with JSpOC to provide data for partners to assess risk
- As with ISS, all visiting vehicles screen their planned maneuvers against debris catalog
- In development of conjunction operations, TOPO has provided expertise in
 - Negotiating ephemeris formats and notification thresholds with JSpOC on behalf of partners
 - Providing primary or backup collision probability calculations during mission
 - *Currently, operational responses are still the responsibility of the operating partner and vary for each vehicle*
- With high levels of vehicle traffic expected for many years, ops standardization might become more important



Implemented Conjunction Improvements for ISS

- ✓ Russian pre-maneuver command verification improved
- ✓ Developed “validity criteria” to ensure good Pc calculations so unnecessary actions aren’t taken
- ✓ Improvements in notification criteria to reduce false alarms
- ✓ Implementation of capability to cancel a DAM almost up to the time of ignition
- ✓ Crew Soyuz “shelter in place” capability for late notifications where DAM not possible
- ✓ Ongoing improvements in orbit determination capabilities at USSTRATCOM/JSpOC



ISS Lessons Learned

- “1844 Incident” (1999) proved the need for a very well-defined process, well-trained people, and software adequate to the task
 - A sequence of errors occurred among all parties, from conjunction identification, to “debris clearing” of the DAM, to failed execution of the maneuver. Actions taken:
 - Ground processes between Houston and Moscow made clearer
 - Russian maneuver command testing implemented
 - NASA and USSTRATCOM began routine familiarization cross-training
- Constant improvements to balance safety and mission viability are beneficial
 - Excessive conjunction notifications from Houston to Moscow early in ISS program caused personnel overwork
 - In response, partners implemented smarter conjunction notification criteria
- Flexibility in planning avoidance maneuvers is key in reducing the likelihood of needing to execute them



ISS vs. Cosmos 2251 Debris

- April 2011 conjunctions with Cosmos 2251 had over 40 registered close passes
- Highest concern TCA changed over time
- 0.5 m/s DAM was executed to protect highest Pc cases
- Scenario shows value of flexible maneuvering capability
- There may be better ways to assess risk for repeaters in the future

TCA (GMT)	TCA-30 (CDT)	U	V	W	R	Time to TCA	Pc
2011 091 (Fri, 01 Apr) 03:41:59.541	2011 089 (Wed, 30 Mar) 04:42 PM CDT	2.6	29.5	-7.7	30.6	44.7	3.54E-13
2011 091 (Fri, 01 Apr) 04:27:40.973	2011 089 (Wed, 30 Mar) 05:27 PM CDT	-2.1	133.1	34.2	137.4	25.9	0.00E+00
2011 091 (Fri, 01 Apr) 05:13:39.612	2011 089 (Wed, 30 Mar) 06:13 PM CDT	2.5	-64.4	16.6	66.5	15.7	0.00E+00
2011 091 (Fri, 01 Apr) 05:59:18.063	2011 089 (Wed, 30 Mar) 06:59 PM CDT	-1.5	106.0	27.1	109.4	27.4	1.90E-10
2011 091 (Fri, 01 Apr) 06:45:16.485	2011 089 (Wed, 30 Mar) 07:45 PM CDT	1.7	-87.4	22.4	90.2	17.2	1.23E-19
2011 091 (Fri, 01 Apr) 07:30:52.375	2011 089 (Wed, 30 Mar) 08:30 PM CDT	-2.7	121.0	30.8	124.9	22	9.61E-06
2011 091 (Fri, 01 Apr) 08:16:51.811	2011 089 (Wed, 30 Mar) 09:16 PM CDT	1.1	-90.9	23.3	93.9	24.2	5.77E-15
2011 091 (Fri, 01 Apr) 09:02:30.236	2011 089 (Wed, 30 Mar) 10:02 PM CDT	-2.1	85.9	21.8	88.6	19.5	2.16E-06
2011 091 (Fri, 01 Apr) 09:48:28.154	2011 089 (Wed, 30 Mar) 10:48 PM CDT	0.4	-107.5	27.4	110.9	25.7	9.66E-08
2011 091 (Fri, 01 Apr) 10:34:06.606	2011 089 (Wed, 30 Mar) 11:34 PM CDT	-1.9	68.5	17.3	70.7	21	1.85E-12
2011 091 (Fri, 01 Apr) 11:20:05.111	2011 090 (Thu, 31 Mar) 12:20 AM CDT	-0.5	-135.5	34.4	139.8	30	0.00E+00
2011 091 (Fri, 01 Apr) 12:05:42.765	2011 090 (Thu, 31 Mar) 01:05 AM CDT	-1.6	53.1	13.4	54.8	22.6	4.96E-17
2011 091 (Fri, 01 Apr) 12:51:41.170	2011 090 (Thu, 31 Mar) 01:51 AM CDT	-1.3	-149.8	37.9	154.5	31.5	0.00E+00
2011 091 (Fri, 01 Apr) 13:37:18.883	2011 090 (Thu, 31 Mar) 02:37 AM CDT	-1.4	39.3	9.9	40.5	24.1	0.00E+00
2011 091 (Fri, 01 Apr) 15:08:54.994	2011 090 (Thu, 31 Mar) 04:08 AM CDT	-1.3	27.0	6.8	27.9	25.6	0.00E+00
2011 091 (Fri, 01 Apr) 16:40:30.795	2011 090 (Thu, 31 Mar) 05:40 AM CDT	-1.3	17.3	4.3	17.9	27.2	0.00E+00
2011 091 (Fri, 01 Apr) 18:12:06.496	2011 090 (Thu, 31 Mar) 07:12 AM CDT	-1.3	8.4	2.1	8.7	28.7	0.00E+00
2011 091 (Fri, 01 Apr) 19:43:42.272	2011 090 (Thu, 31 Mar) 08:43 AM CDT	-1.3	2.0	0.5	2.5	30.2	0.00E+00
2011 091 (Fri, 01 Apr) 21:15:17.857	2011 090 (Thu, 31 Mar) 10:15 AM CDT	-1.2	-1.8	-0.4	2.2	31.7	0.00E+00
2011 091 (Fri, 01 Apr) 22:46:53.255	2011 090 (Thu, 31 Mar) 11:46 AM CDT	-1.1	-3.7	-0.9	4.0	33.3	0.00E+00
2011 092 (Sat, 02 Apr) 00:18:28.483	2011 090 (Thu, 31 Mar) 01:18 PM CDT	-1.0	-3.3	-0.8	3.5	34.8	0.00E+00
2011 092 (Sat, 02 Apr) 01:50:03.495	2011 090 (Thu, 31 Mar) 02:50 PM CDT	-0.8	-1.1	-0.3	1.4	36.3	8.96E-20
2011 092 (Sat, 02 Apr) 03:21:38.420	2011 090 (Thu, 31 Mar) 04:21 PM CDT	-0.5	2.5	0.6	2.6	37.8	4.28E-09
2011 092 (Sat, 02 Apr) 04:53:13.332	2011 090 (Thu, 31 Mar) 05:53 PM CDT	-0.2	7.5	1.8	7.7	39.4	8.58E-05
2011 092 (Sat, 02 Apr) 06:24:48.222	2011 090 (Thu, 31 Mar) 07:24 PM CDT	-0.2	15.2	3.7	15.7	40.9	1.31E-04
2011 092 (Sat, 02 Apr) 07:56:22.833	2011 090 (Thu, 31 Mar) 08:56 PM CDT	-0.3	25.9	6.3	26.7	42.4	7.54E-05
2011 092 (Sat, 02 Apr) 09:27:57.249	2011 090 (Thu, 31 Mar) 10:27 PM CDT	-0.3	38.5	9.3	39.6	43.9	1.44E-04
2011 092 (Sat, 02 Apr) 10:59:31.460	2011 090 (Thu, 31 Mar) 11:59 PM CDT	-0.2	53.6	12.9	55.1	45.5	2.25E-06
2011 092 (Sat, 02 Apr) 11:45:25.418	2011 091 (Fri, 01 Apr) 12:45 AM CDT	-8.6	-19.7	4.8	22.0	76.7	3.54E-13
2011 092 (Sat, 02 Apr) 12:31:05.538	2011 091 (Fri, 01 Apr) 01:31 AM CDT	-0.1	70.4	16.9	72.4	47	7.01E-14
2011 092 (Sat, 02 Apr) 14:02:39.616	2011 091 (Fri, 01 Apr) 03:02 AM CDT	-0.2	88.9	21.2	91.4	48.5	0.00E+00

Summary of ISS conjunctions with object 34443

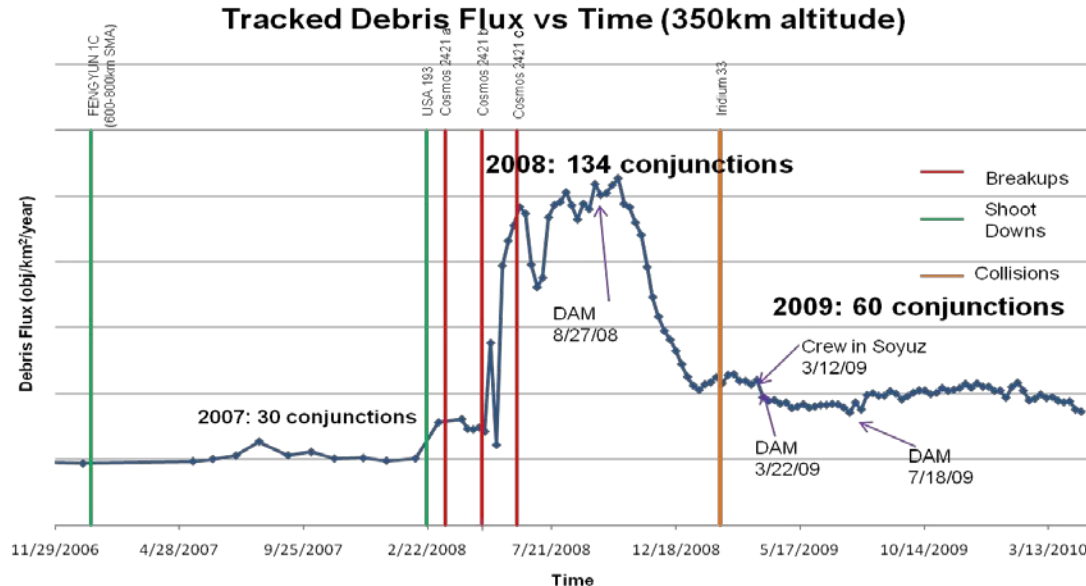


Lesson: Conjunction Frequency vs. Debris Flux

❑ Frequency of notifications varies substantially depending on debris population at vehicle altitude. Number of ISS conjunctions:

- ❖ 390 from ISS first element launch through July 2008 (~0.8 conjunctions per week)
- ❖ 200 from August 2008 through April 2009 (~5 per week)
 - COSMOS 2421 – Three breakup events in 2008: 14-March, 28-April, 9-June
 - COSMOS 2251 / Iridium 33 collision 10-February-2009
- ❖ 191 from May 2009 through present (~2 conjunctions/week)

❑ As ISS raises permanent altitude from 350 km to 410 km this year, conjunction frequency may increase





Conjunction Operations Considerations for ISS

- Maximum consequences if we fail
- Size of vehicle: 140 meters between farthest points of solar arrays
- Low altitude, high-drag environment means making assessments for “correct” operations difficult
 - Late-notifications (“false negatives”)
 - Unnecessary concern for some objects
 - Highly erratic predictions for small debris
 - High Pc for objects very far away (>100 km)
- Many requirements on ISS orbit to satisfy visiting vehicle success
 - Space Shuttle rendezvous on flight day 3
 - Space Shuttle maximum rendezvous altitude
 - Soyuz/Progress rendezvous on FD3; daylight landing in Russian zone
 - HTV perigee limits
 - ATV mission design limits
 - Future vehicle requirements?
 - All of these must be considered when designing a DAM for safety



Improvements for the Future

- Improving covariance realism
- Implementing late-notification DAM capabilities
 - Allows critical decisions to be made when uncertainties are small
- Solving the repeating conjunction problem
- Developing covariances for perturbing events on ISS
 - Docking/undocking
 - Reboost
 - Propulsive attitude maneuver
- Adapting operations/resources to an increasing debris population
 - Future collisions, satellite breakups
 - Improved tracking capability may find more, and smaller, objects
- Overhaul criteria to determine if a P_c is valid
- Investigate using covariance-based debris screening (instead of fixed volumes)